HIRWG Minority Report

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1. Executive Summary

This minority report exists because we think that the exclusive focus of the majority of the group on high-resolution numerical modeling of hurricane dynamics is not consistent with our own perception of the best approach to improved hurricane intensity forecasts. Moreover, we are convinced that such an approach is beyond NOAA's capacity to implement and will remain so for many years. It represents a slow evolution of the status quo with respect to improved predictions, data assimilation, and observational methods; one which has produced little or no progress in hurricane intensity forecasts for well over a decade. As outsiders to the meteorology community, we believe a more radical approach is both required and feasible.

The present report reflects our sense of where NOAA's priorities should be placed. The underlying philosophy that guides the discussions and recommendations in this report can be stated as follows: Pursuit by NOAA of knowledge of the characteristics of any tropical cyclone is in aid of more timely and accurate forecasting of a few basic macroscopic properties. The pursuit of knowledge about additional characteristics of a tropical cyclone can be justified only to the extent that it leads to improvements in these forecasts. The more simply, directly, expeditiously, and economically that NOAA may meet its intensity-forecasting responsibilities, adequately to serve the needs of the multiple user communities dependent on those predictions, the better. In this sense, NOAA may be regarding as bringing a practical, engineering-like outlook to the challenge of monitoring and forecasting of hurricane intensity.

The priorities summarized below reflect a balance between existing numerical models, simplified approaches incorporating significant mathematical analysis, a greatly enhanced role for laboratory scale experiments, and the introduction of unmanned aerial vehicles for use as a major data source. We believe much more emphasis needs to be placed on fostering a diversity of ideas and approaches to hurricane forecasts, rather than converging on a single officially approved numerical model. To this end, we believe that a new organization, a National Hurricane Research Laboratory, should be created, and a significant fraction of the resources that might otherwise go into computer upgrades should be devoted to hiring and/or retaining the professional staff needed to carry out these ideas. Our recommendations are divided into four parts.

Modeling and Prediction: Targeted Research for Rapid Transfer to Serve NOAA Operations (Section 2)

- **Problem:** Current NOAA computing power and planned upgrades will not permit existing numerical mesoscale models to be used at the spatial scale needed to provide accurate operational forecasts of key hurricane intensity parameters, particularly in the inner-core region and boundary layer of a given tropical cyclone. Moreover, the input information required to run these codes is seriously incomplete or flawed, particularly when initializing a simulation and at the air-sea interface.

- **Recommendation:** NOAA should develop a procedure for coupling existing mesoscale numerical models in the outer regions of a tropical cyclone with simpler numerical/analytical predictive tools developed specifically to describe the inner core and boundary-layer regions, with a view to employing these models in operational forecasts.

- **Problem:** The NOAA Environmental Modeling Center has advocated a broadening of the utilization of the National Hurricane Center's limited modeling and observational resources. This would result in the monitoring of all tropical disturbances, beginning at an early, weak stage -- even though most tropical systems will fizzle.

- **Recommendation:** NOAA should continue to focus resources allocated for operational hurricane-intensity forecasting, and for research targeted to upgrade that forecasting, tightly on hurricane-like systems, especially higher-speed vortices closer to landfall.

- **Problem:** The demands of detailed numerical simulations under development for prediction of the intensity of a hurricane appear to be so excessive that a single run will consume all of the existing or planned NOAA computing resources allotted for that purpose. Furthermore, calls for the coupling of ocean phenomenology with atmospheric phenomenology would seem to exacerbate computing limitations in an era of ensemble forecasting.

- **Recommendation:** NOAA should avoid the use of very high-resolution numerical models, substituting simpler analytic/numerical methods to represent critical smaller-scale phenomena. NOAA should also tentatively proceed with hurricane-intensity-forecast models not incorporating sea/air coupling or use simple models to represent the coupling, especially since the key sea/air-transfer formulae will remain largely empirical.

- **Problem:** Contemporary computer calculations leave practically important information about what is experienced on the much finer scale of hurricane-exposed individual structures at ground level largely unexplored. Moreover, the wind stress acting on the ocean to generate the storm surge and wave field of landfalling tropical cyclones is related to the dynamics at 10-m altitude, but adequate knowledge of the dynamics in the surface boundary layer under a high-speed vortex is not furnished by such calculations.

- **Recommendation:** NOAA ought to execute, efficiently in real time, useful estimation of the "secondary effects" of a landfalling tropical cyclone, by adopting a model for each secondary effect that is accurate and simplistic, and by using a compact representation of the low-level wind field and pressure field of the landfalling vortex.

Observation and Data Collection (Section 3)

- **Problem:** The two highest-priority challenges for operational forecasting of tropical-cyclone intensity are identified as: (1) anticipation of the onset of rapid large-magnitude intensification/weakening, and (2) anticipation of the onset of eyewall-replacement cycling. Novel observational methods will be required to obtain the data needed to address these issues.

- **Recommendation:** Owing to intensive investment through resources of the Department of Defense, the use of Unmanned Aeronautical Systems (UASs) for the remote sensing of hurricanes is deemed of *high promise.* NOAA should form an internal study group for the transfer and deployment of high-performance UASs as they become available from the US Military. This study should include determination of proper instrumentation, site selection, and crew training, with a view to achieving operational status within 3-5 years.

Laboratory Experiments (Section 4)

- **Problem:** Although the contribution of at-sea experiments to the understanding of tropical-cyclone phenomenology is long established, at-sea experiments are costly to undertake, entail prolonged planning and drawn-out data reduction, and occur only at long intervals. Other challenges of at-sea experiments include difficulty in defining conditions, an often-harsh environment for sensors and platforms, and inflexibility to respond to unexpected observations.

- **Recommendation:** NOAA should adopt a general policy of requiring the integration of laboratory-scale experimentation with every "field"-experiment initiative as a lower-cost way of evolving tentative theses, to be confirmed, modified, or rejected in subsequent at-sea testing.

- **Problem:** Progress in intensity forecasting has been virtually nil during the past few decades, during which a large ocean heat source has been postulated as the "driving mechanism" for intensification in most hurricane modeling. Examination of an alternative hypothesis would be useful.

- **Recommendation:** Measurements by Mark Donelan and his associates in a combination wind tunnel and programmable wave tank (with subsequent support from data taken at sea as part of the CBLAST project), show that the drag coefficient at the air/sea interface does not continue to increase with the atmospheric-wind speed for storm-force and higher winds. These experiments in the laboratory ought to be extended to encompass heat and mass transfer from slightly warmed water to moist air flowing above, to resolve the long-standing uncertainty about how the turbulent exchange coefficients for temperature and moisture vary with wind speed. The potential uses for a suitably instrumented wind-wave tank include the furnishing of a vast amount of data about the nature of an air boundary layer evolving over a sheared layer of water. Moreover, NOAA should convene a study group to produce concrete recommendations about a feasible design for a circular wind driven wave tank of order 20-m diameter, to create a swirling flow boundary layer over a warm water pool (a laboratory simulation of the very-low-level flow in a hurricane).

Organizational Issues (Section 5)

- **Problem:** The absence of a focus for hurricane-related efforts within NOAA has resulted in many ongoing tropical-cyclone-related activities being underfunded, spatially disperse, and sometimes isolated from (and impractical for) serving the objective of rapid transition to operational forecasting of hurricane track and intensity.

- **Recommendation:** A National Hurricane Research Laboratory should be established (more accurately, restored) at a single location in Miami, with responsibility for all hurricane-related research, including analysis, numerical modeling, instrumentation, and large-scale laboratory experiments. Organizational units currently located elsewhere that fit into the NHRL should be relocated. The NHRL should be located as close to the operational hurricane forecast group (NHC) as possible. It should be endowed with resources to hire a professional staff capable of supporting these activities, as well as host academic researchers and long-stay visitors from other NOAA laboratories on a regular basis. In recruiting the staff for NHRL, NOAA is advised to contact applied physicists, mechanical engineers, and others from the broader fluid dynamics community.

2. Modeling and Prediction: Targeted Research for Rapid Transfer to Serve NOAA Operations

2.1 Statement of the intensity-forecast problem for hurricane-like systems: prioritizing forecasts of more-intense systems

In accord with the focus incorporated in its designation, the National Hurricane Center (NHC) should concentrate its finite modeling and observational resources exclusively on tropical systems that already Typically, every six hours (and more often as deemed necessary) for any tropical system in the western North Atlantic or eastern North Pacific of tropical-depression intensity or greater (where a tropical depression has both a closed circulation and deep convection), the operational-forecasting arm of NOAA, the National Hurricane Center (of the Tropical Prediction Center, in Miami, FL) updates its forecast of track and intensity for the next five days (i.e., 120 h). After landfall, defined as the time when the center of the storm comes ashore, further prediction becomes the responsibility of the local Weather Forecast Office of the National Weather Service. Attention here is focused on NOAA forecasts of intensity, which typically predict the following (and only the following) macroscale properties of the tropical cyclone under scrutiny: the sea-level pressure at the center of the system, the maximum one-minute-averaged wind speed in the lower troposphere (nominally, 10-m altitude) in the core of the vortex, the lateral distance from the center of the vortex to the onset of sustained hurricane-magnitude wind, the lateral distance to the onset of sustained storm-magnitude wind, and the lateral distance at which winds subside to the ambient [i.e., the (lateral) scale, or “size”, of the vortex]. At and after landfall, this wind-and-pressure forecast is complemented with prediction of rainfall (Halverson 2005), storm surge (Rosenfeld 1997), and wave height (Davis and Paxton 2005), and tornadogenesis hazard (Curtis 2004).

The underlying philosophy that guides the discussions and recommendations in this report can be stated as follows: Pursuit by NOAA of knowledge of the characteristics of any tropical cyclone is in aid of more timely and accurate forecasting of the above-enumerated macroscopic properties. The pursuit of knowledge about additional characteristics of a tropical cyclone can be justified only to the extent that it leads to improvements in these forecasts. The more simply, directly, expeditiously, and economically that NOAA may meet its intensity-forecasting responsibilities, adequately to serve the needs of the multiple user communities dependent on those predictions, the better. In this sense, NOAA may be regarding as bringing a practical, engineering-like outlook to the challenge of monitoring and forecasting of hurricane intensity.
have hurricane-like properties. This outlook confines attention to well-organized depressions or stronger systems, particularly those closer to landfall. The relatively recent extension of forecasting to 120 h, undertaken largely in response to Navy requests (which the Navy may be well able to fulfill for itself), should not lead to expending constrained resources on weak nascent tropical systems, most of which will fizzle. It seems advisable to let nature do the preliminary sorting among the many weak disturbances arising (through several different physical mechanisms) in hurricane season. There is little justification to monitor atmospheric perturbations beyond what satellite systems routinely furnish. How the tropical ambient is maintained, and investigation of the multivaried pathways by which incipient disturbances arise and sometimes grow in that ambient, are regarded as an unwise diversion of overtaxed NHC manpower and equipment. Moreover, since the destructiveness of a tropical cyclone seems to vary roughly as its power (i.e., as the cube of its peak sustained wind speed) and its size, there appears to be a particularly large return on accurate timely forecasting of more intense hurricanes, especially large high-speed vortices near landfall. Thus, the priority to be accorded tropical systems among those that are monitored and for which predictions are undertaken is self-evident.

This section is completed with a discussion of how the practical need for concise characterization of tropical-cyclone intensity is met by NOAA. Despite the limitations and incompleteness, concise characterization of current tropical-cyclone intensity, and concise prediction of future intensity, is, and ought to continue to be, presented primarily in terms of the peak sustained-wind speed in the lower-troposphere portion of the vortex. Because of well-understood convention, presentation for the general public of the peak sustained-wind speed should continue to be by binning into classifications with standard definitions: depression, tropical storm, hurricane (which is then subdivided into categories 1 and 2), and major hurricane (which is then subdivided into categories 3, 4, and 5). However, the thresholds between depression and tropical storm, between hurricane and major hurricane, and among categories are arbitrary and without physical basis. Moreover, the numerical values of the thresholds are not universally familiar to the public. Also, the current standard statement of the widely adopted Saffir-Simpson categorization (Simpson and Riehl 1981; Sheets and Williams 2001) associates particular wave height, storm surge, and rainfall with each category of intensity. In fact, each of these effects depends on multiple parameters in addition to the peak sustained-wind speed (and/or the central sea-level pressure deficit from ambient). So the current attempt to "pre-package" associate effects is oversimplified and often error-prone. Statements presently affixed to hurricane categories, regarding associated effects such as wave height, storm surge, and rainfall, should be discarded as unreliable. Since a very small increment/decrement may alter classification of a system, therefore, for more highly informed members of the public, an actual numerical value of the peak sustained-wind speed should be given along with the bulk classification of the tropical cyclone, and a quantitative estimate of the accuracy (error) of the numerical value should also be given.

2.2 Numerical models and resolution

Numerical models are the dominant forecasting tools for both global and mesoscale weather prediction in general and hurricane track forecasts in particular. Such models are also used to attempt hurricane intensity forecasts, with unsatisfactory results to date. Indeed, the inability of such codes to reliably predict hurricane intensity is responsible for the formation of the HIRWG. The problems that arise in hurricane intensity forecasts with *any* numerical model are closely tied to the *spatial resolution* that can be achieved when using the model. To understand this, it is necessary to summarize how such models work.

In a numerical forecast model, the state of the atmosphere is described by dividing the portion of the atmosphere (the domain) to be studied into a large number of smaller volumes. Within each volume the quantities to be predicted (velocity components, temperature, pressure, water content, radiant intensity, etc.) are assumed to be roughly constant. The horizontal and vertical dimensions of each such volume (the grid size) are chosen to try to simulate the phenomena deemed to be important for forecast purposes. The laws of physics controlling these phenomena are approximated within each of these volumes by relating the change in each physical quantity (mass, momentum, energy, etc.) over a short period of time to fluxes of these quantities across the boundary, together with any changes to physical properties due to processes within the volume. Since the real atmosphere changes continuously on *all* length and time scales, the fidelity with which a numerical model can represent the actual physical process of interest is highly dependent on the ratio of the linear dimensions of the volume to the length scale on which the process of interest occurs in the atmosphere. The *spatial resolution* associated with a numerical model is the smallest length associated with a physical process that can be predicted with reasonable accuracy using that model. This is typically several times larger than the dimensions of the volume employed in the model. It should be understood that these concepts are *not* peculiar to meteorology. They hold for any numerical model of a physical system that can be described by classical continuum physics. Examples include aerodynamics, combustion, and structural mechanics.

All numerical weather forecasting adopts a strategy that in other communities is known as "Large Eddy Simulation" (LES). The main point is that all the possible length scales on which the processes that determine the state of the atmosphere take place are divided into two parts. The phenomena occurring at larger scales are calculated explicitly, using a variety of numerical techniques derived from the field of Computational Fluid Dynamics (CFD). While these techniques introduce errors of their own, this does not produce uncertainty in the same sense as the spatial-resolution issues described above. The techniques are ultimately convergent, in the sense that they will produce a unique result if the smallest length scale to be resolved could be reduced to zero. However, the vast majority of the length scales at which physical processes occur in the atmosphere are too small to be resolved. This means that empirical relations must replace a detailed computation of the state of the atmosphere on these "subgrid" scales. The prediction of subgridscale phenomena cannot be improved by performing an ensemble of calculations, each with a different subgrid model. However, it is possible (indeed this is the rationale behind LES in any field in which it is employed) that the large-scale features of the hurricane dynamics are not sensitive to the details of the small-scale phenomena. This property enables useful forecasts of the gross features of the hurricane.

Nonetheless, at least some of the difficulties associated with predicting hurricane intensity arise from the fact that some phenomena that must be predicted accurately occur at length scales either at or below the resolution limit of the LES calculations used to simulate the hurricane. This is particularly true for the dynamics of the eyewall and the boundary layer lying above the air-sea interface. Moreover, the physical processes occurring in both cases are poorly understood. Thus, it is difficult to produce a subgridscale empirical model or set of parameters to represent the influence of the eyewall or boundary layer (including the air-sea interface) because the basic understanding needed to develop such a model does not exist (e.g., Morrison et al. 2005). The alternative, a numerical model detailed enough to resolve the features we know are important (let alone those we are not yet aware of) is beyond the capacity of current computers and will remain so for many years. *Given this situation, the degree to which an ensemble of calculations will remove the deficiencies inherent in a flawed model is moot*. We do not yet have the understanding to develop a subgrid model worth using for the air-sea interface or eyewall, and we do not have computing capacity to perform the ensemble of calculations that would be needed if we had such models.

Some important conclusions regarding simulations of hurricane dynamics follow immediately. The eyewall of a hurricane plays an important role in the intensification of hurricanes. Typically, an eyewall is less than 10 km in thickness. Thus, any simulation using a grid size whose horizontal dimensions are roughly this size or larger will be unable to predict the dynamics of such processes as the eyewall replacement cycle. It is almost certain that any numerical simulation that successfully predicts eyewall dynamics will need to use grid sizes with horizontal dimensions in the 1-2 km range or smaller (e.g., Klemp and Skamarock 2004). Both the existing GFDL Hurricane Prediction System and its potential NCEP replacement, the HWRF code, which are described briefly below, use grid sizes of approximately 10 km horizontal dimensions.

Other issues arise when numerical models are the principal forecasting resource. Since the spatial domain used to simulate the hurricane is finite, information must be provided at the horizontal boundaries of the domain. These *boundary conditions*, together with the *initial conditions* needed to start the forecast, imply reliable and timely sources of observational and/or computed data from global forecasts. The process of *data assimilation* into the computer model used to provide the forecast is a rapidly evolving field in its own right. Until these procedures are refined to the point where the prediction errors associated with imperfect and incomplete data are well understood, the numerical modeling process must remain unreliable. Finally, the physical processes that control the interaction between ocean and atmosphere are imperfectly understood. From the point of view of a numerical forecast of the hurricane dynamics, it is the most poorly understood of all the boundary conditions. The information needed to describe the *air-sea interaction* is much more likely to come from *laboratory-scale experiments* than from computer models.

The GFDL Hurricane Prediction System has been used since 1995 to provide guidance for operational track and intensity forecasts for NHC (Shen 2005). According to a 2001 GFDL report maintained on its website to this date, "Although the model has shown great skill in track prediction, the GFDL Hurricane Prediction System exhibits small track biases and rather large intensity biases (Bender and Ginis 2000). Indeed, in spite of a steady improvement in tropical cyclone track forecasting over the last two decades (Lawrence et al. 1997), there still appears to be little skill in predicting hurricane intensity changes." The same comments were made by GFDL after the 2003 hurricane season. Assuming the motivation behind the formation of the HIRWG is credible, little has changed with respect to operational hurricane intensity forecasting, although many changes have been implemented in the GFDL code. Despite this, the code continues to be supported and upgraded by GFDL, which is committed to maintaining this support for at least the next few years.

More recently, NCEP has undertaken the development of the Hurricane Weather Research and Forecast Model (HWRF) for operational forecasts. Current plans assume this model will become operational in 2007, with an ultimate goal of replacing the GFDL code at some point in the future. This computer model is an outgrowth of the meteorology community Weather Research and Forecast (WRF) code (N. Surgi, presentation to the HIRWG, Sept 1-2, 2005). According to the WRF website, "The effort to develop WRF has been a collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL)), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, Oklahoma University, and the Federal Aviation Administration (FAA). WRF allows researchers the ability to conduct simulations reflecting either real data or idealized configurations. WRF provides operational forecasting a model that is flexible and efficient computationally, while offering the advances in physics, numerics, and data assimilation contributed by the research community."

While GFDL has offered some support to NCEP with the implementation of the HWRF code, the motivation driving the GFDL agenda appears to be the development of a global high-resolution numerical model that will ultimately supersede all other numerical forecasting codes, including the WRF code and its various offshoots. While this is a laudable goal, the contribution of any such code to hurricane intensity forecasting will be negligible for decades. The grid sizes that can be employed in current global operational forecasts extend many tens of kilometers in the horizontal directions. This is much too crude to describe most hurricane phenomena. Indeed, it provides much worse resolution than that of any of the numerical models currently used for hurricane forecasts. It will require computing power many orders of magnitude beyond anything accessible to the meteorology community to provide global forecasts with the spatial resolution needed to furnish useful predictions of hurricane intensity.

The numerical modeling problem that NOAA needs to resolve can now be summarized as follows: The existing operational and potential near-term replacement hurricane forecast models are flawed because of the inadequate spatial resolution that must be employed, given existing computer technology and resources. The promised future models (high-resolution global forecasts) are so far off in the future that they are irrelevant to any plans that the current NOAA leadership can make. The input information required to run these codes is seriously flawed, particularly when initializing a simulation and at the air-sea interface. Credible remedies for these problems will not come from the numerical modeling community alone. Unless a sophisticated blend of analysis (theory), laboratory experiment, and numerical modeling is concocted, the hurricane intensity problem will remain exactly where it is today: an unresolved issue looking for new ideas.

2.3 Modeling dilemma in an era of ensemble forecasting

Operational experience with numerical weather prediction on a variety of spatial and temporal scales indicates the superior performance attained with ensemble forecasting (Lighthill 1998; Emanuel 2003; Palmer et al. 2005). The robustness of forecasts to uncertainties in parameterization of subgridscale processes in terms of gridscale variables, and to uncertainties in initial/boundary/update data, is found in practice to be better assessed if the multiplicity of forecasts is furnished by several independent models, as opposed to many runs with perturbations of a single model. Of course, this preference is predicated on the availability of a multitude of well-performing models for the forecasting at hand. For each of these models, the required initial/boundary/update data must be available, and the key output for NOAA forecasting must be readily extractable. Most importantly, if the demands by a single code for prediction of the intensity of a hurricane vortex are so excessive that a single run consumes almost all the NOAA computing allotment, then completion of that solitary run within the allotment is a Pyrrhic accomplishment, from the viewpoint of ensemble forecasting. As already noted, it is certainly a Pyrrhic accomplishment if the execution within the computing allotment is achieved only by adoption of a gridding too gross to resolve essential features of the hurricane structure, such as the surface boundary layer and eyewall. Since the execution of a single run by a single code for hurricane-intensity forecast should lie well within the NOAA computing allotment, a premium is placed on the simplicity of the prediction model (and speed of execution), accuracy of the forecasts being at all comparable with that of alternative more-computationally-demanding models.

Implementation of ensemble forecasting is strained by models that begin as early as possible in the lifetime of a tropical system and adopt a highly comprehensive formulation. A problem with this approach is that it requires adoption of parameterizations of uncertain validity; introducing such detail may introduce error, rather than improvement. A typical response to shortfall in prognostic performance is to incorporate phenomena previously relegated to marginalia (as exemplified by the recent decision to include more condensed-phase species in the HWRF code in response to disappointing performance of the GFDL code). Under such response, for existing levels of computing power, inadequate resolution is further compromised to permit inclusion of probably even more dubious parameterization… a degenerative cycle.

Calls for the coupling of ocean phenomenology with atmospheric phenomenology also would seem to exacerbate computing limitations in an era of ensemble forecasting. During the passage of a hurricane over a patch of ocean, churning induced by the vortex leads to mixing of the colder abyssal water with the warmer water confined to the uppermost layer of the ocean. The redistribution of heat within the ocean as a consequence of this mixing results in lower temperature in the uppermost layer, especially if the hurricane is slowly translating and passage is prolonged, and especially if the uppermost layer is thinner so there is less warm water at the start. How much the uppermost ocean layer cools is at issue, but there is no physical mechanism for this layer to be significantly warmed by the passage of a hurricane. Thus, neglecting the *thermodynamic* consequences of ocean response to an overlying hurricane means that the sea-to-air transfer of thermal energy may be overestimated. This overestimate leads to a prediction that is an upper bound on hurricane intensity. Since erring on the side of caution seems the more judicious (if possibly more expensive) policy, omitting a detailed description of ocean phenomena may be a reasonable path. In any case, prediction of the crucial thermal-energy transfer occurring in the immediate vicinity of the sea/air interface is unlikely to prove reliable. The key sea/air-transfer formulae will remain largely empirical, and this will not change by incorporating ocean coupling in simulations.

Tentatively proceeding without sea/air coupling, except to the extent needed to model the *dynamics* of the air-sea interface, is consistent with an approach that seems well deserving of consideration (and that is, in fact, developed in the next section). The approach is to adopt the simplest model within reason, and to add complication only as warranted by comparison of predictions with observations. We believe that all the contribution to intensity forecasting to be elicited from relatively simplistic models has yet to be realized. Given the further advantages expected to be gleaned from the use of ensemble forecasting, the promise of simplistic modeling has yet to be realized, and now even more worthy of pursuit.

2.4 Simplified models as predictive tools

At present, at least one commonality is shared among the spectrum of hurricane-intensity-prediction models that are, or ought to be, available for trial as candidates to guide NOAA operational forecasters. The commonality is shared whether a model stems from basic physical laws or from statistical correlation (empirical regression), or some provenance in between. That commonality is the need for extensive, prolonged “tuning” against observational data before the model is operationally useful. Consequently, all the alternate models (including numerical models), to some extent, become either more elaborate or less elaborate curvefits to the same data base, and may perform comparably when employed for prediction.

Motivations for preferring the simpler candidates among the resulting semi-empirical models often include shorter run times, more modest computer-memory requirements, less demanding computer-processing requirements, smaller input-data needs (whether related to initial conditions, boundary conditions, or updated internal conditions), greater ease of portability and modification, more facile extraction of key results, etc. “Balance” after initiation of computation typically is achieved more rapidly in a simpler vortex model, so “assimilation” of intermittently furnished update data, variable in its completeness from refresh to refresh, may be feasible via re-initialization of the model. However, a point deserving particular emphasis is that a simpler model stemming from approximations to the basic physical principles still may be anticipated to furnish predictions for every one of the macroscopic properties that appear in a standard NOAA intensity forecast. Thus, a simpler model may be fully viable as a predictive tool for hurricane-intensity forecasting. Any implication that many simpler models provide limited results, and are inherently less adequate than a so-called “more detailed” model for serving standard NOAA intensity forecasting, lacks any basis in reality.

Moreover, a simple operational model for intensity forecasting offers the additional advantage that it might be readily utilized for fast-turn-around, systematic, exploratory investigations of high-priority research topics. Two current research topics of high priority for intensity forecasting are: (1) rapid intensification/weakening of an already well-organized tropical cyclone (e.g., a change in excess of 20 kts in peak sustained lower-tropospheric wind speed over a time span on the order of 12 h); and (2) eyewall-replacement cycling, whereby a moderate-intensity hurricane weakens as a new eyewall forms further from the axis of rotation and supplants the prior eyewall situated closer to the axis of rotation (Willoughby 1990, 1998, 1999; McNoldy 2004). (Sometimes, the new eyewall converges toward the axis of rotation, and the hurricane re-intensifies, to complete the cycle; indeed, the full cycle occasionally has been repeated, provided landfall or other event does not intervene.) The advantage of an operational model (or a modestly modified operational model) for such targeted phenomenological research is a rapid transition of new findings to practical forecasting. Indeed, this is part of the justification for the widespread deployment of the WRF model, as noted above. In fact, this advantage accrues to any widely used model, whether or not it is based on CFD techniques.

Additionally, a higher return accrues to NOAA’s product-user community from accurate forecasting of the intensity of stronger tropical cyclones. Thus, focusing attention on transitions in already intense hurricanes, without having to trace the early stages of their development is appealing. In the Atlantic basin (and perhaps others as well), roughly one in two hurricanes evolves to become a major hurricane, and, tracking back a bit, roughly one in two tropical storms evolves to become a hurricane. For such mature-stage transitions, examination of internal vortex dynamics may often suggest accessible observables that portend the onset of intensification or weakening, perhaps even the time scale for the change in intensity. Searching for a discriminant (regarding a transition between two seemingly stable configurations) with a one-in-two likelihood of occurrence appears a more promising pursuit than searching for discriminants for weaker, less hazardous, probably remotely sited tropical disturbances with only a small (perhaps 10%) chance of becoming a hurricane. Traditionally, use of detailed models has been characterized by the investment of much effort in incipient-stage tracking of tropical systems, and by computationally intensive scrutiny of only a limited number of particular tropical systems. A simple model seems inherently more adaptable, and flexible for application to *both* particular tropical cyclones with today's level of insight, *and* to systematic exploration of tropical-cyclone phenomenology to achieve a higher level of insight for future (hopefully upgraded) intensity forecasting.

2.5 Interfacing with secondary-effects forecasting (surge/waves; rainfall; tornadoes)

At present, the operational forecast for vortex intensity is focused on predictions of: (1) the sustained (time-averaged) wind field, as a function of time into the future and of lateral and vertical position in the storm -- with emphasis on the peak sustained wind speed at nominally 10-m height; and (2) the pressure field, also as a function of time into the future and of lateral and vertical position in the storm -- with emphasis on the minimum sea-level pressure, reasonably anticipated to be reached at the axis of rotation of the vortex. Of course, this prediction is incomplete because: it is given on the scale of the finite-differencing grid of the computer calculation (never more refined than 10 km), so that, for example, practically important information about what is experienced on the much finer scale of individual structures at ground level remains largely unexplored; and the unsteadiness (gustiness) of the flow is very crudely addressed by rule-of-thumb "enhancement" factors. Structural aerodynamics in a hurricane vortex clearly needs to be addressed in the future, and technical expertise and laboratory facilities outside the meteorological community ought to be enlisted in this undertaking.

More immediately, for landfalling hurricanes, most of the loss of life and property in the vicinity of the coastline is attributed to the storm surge and wave height. Inland, most of the loss of life and property is attributed to rainfall runoff and sometimes tornadogenesis. While the decoupling of effects is a simplification, prediction of surge/waves, rainfall, and tornadoes is often undertaken sequentially, after a forecast of wind and pressure is in hand (Flather 2003).

A possible alternative or complement may be the efficient calculation in real time of the "secondary effects" for the combination of parameters pertinent for the particular hurricane landfall that is confronting operational forecasters. This real-time calculation seems feasible if each secondary-effect model is relatively simplistic (Kaplan and de Maria 1995), and if the wind field and pressure field of the landfalling vortex is compactly represented for use in that model. Any profession of meticulous accuracy achieved by a detailed model must recognize the inherent limitations imposed by the spatial and temporal resolution that can be achieved using an operational numerical model. Alternatively, a simple model may already generate the wind and pressure fields in forms tractable for use in each secondary-effect model.

It warrants comment that the wind stress acting on the ocean to generate the storm surge and wave field typically is related to the dynamics at 10-m altitude. Thus, estimation of that wind stress requires knowledge of the dynamics in a *surface boundary layer* under a *high-speed* vortex. Results obtained using a relatively simple boundary-layer model focused on the near-surface region may prove more accurate than results obtained using the output of an elaborate numerical model with inadequate spatial resolution near the surface.

3. Observation and Data Collection

3.1 Reconciling the data needs of hurricane models with what is typically available; identifying gaps

A juxtaposition of the temporal and spatial scales of a tropical cyclone (possibly lasting weeks, spanning many hundreds of kilometers laterally, at any instant of time, moving hundreds of kilometers per day and extending vertically through the entire tropical troposphere), and the monitoring that is now (or soon will be) feasible in the Atlantic and eastern North Pacific, indicates wide discrepancy between the data that are desired for model input/model validation and the data that are collected. Data collection is often characterized by: a few reconnaissance "legs" flown through the vortex every six hours, every three hours for a vortex projected to be within 72 hours of landfall, by instrumented aircraft maintaining an altitude of around three kilometers; a typically slant-view overpass by a passive-sensors-carrying sunsynchronous satellite at about 800-km altitude, at best every four hours, the vortex remaining within view for not much more than 10-15 minutes; every-half-hour-updated monitoring by a geostationary satellite at 36,000 km -- its (currently 3-km-resolution) visual and infrared sensors unable to penetrate cloud tops to probe states within and below, and its microwave sensors unable to penetrate heavy rainfall to elucidate states within and below; a few moored ocean buoys that may or may not intersect some part of the translating vortex (Cione et al. 2000); shore-based radar with limited range seaward; possibly one-or-two NOAA research aircraft temporarily reassigned to operational function; and possibly one-of-a-kind NASA tropical-environment-research spacecraft that may or may not still be functioning. The satellites, radar, buoys, and research aircraft serve multiple purposes, many (if not most) of the purposes being not hurricane-related, and only Air Force reconnaissance/surveillance aircraft are dedicated exclusively to tropical-cyclone observation. The unique capacity of aircraft to travel rapidly to the vortex, and then to linger for a few hours within (or in the immediate vicinity of) the vortex, is today so taken for granted that value of this type of asset is well worthy of explicit note.

Clearly, continuous simultaneous measurement of all the state variables at all positions in and near the vortex is impractical, so what subset of such observations should be emphasized to assist models in providing guidance for operational forecasting of tropical-cyclone intensity? We believe that efficient modeling is not just a formal exercise in computer implementation of a numerical analysis of a uniformly valid formulation of a boundary/initial-value problem. In our view, a more inclusive and more general formulation is not necessarily superior to a less inclusive and less general formulation. It helps to have a tentative thesis, to be modified as warranted by results, of how tropical-cyclone structure is sustained [we bypass the nascent stage(s)], and how that structure may evolve, with consequences regarding intensification or weakening.

Progress in intensity forecasting has been virtually nil during the past few decades, during which a large ocean heat source has been postulated as the "driving mechanism" for intensification in most hurricane modeling. Thus, it would be useful to examine an alternative hypothesis. Explicitly, we theorize that the heat and moisture already present in a convectively unstable tropical ambient is being, or has been, "captured" in a cyclotrophic-like balance, for a hurricane-like vortex to become organized (Carrier 1971b). This gradually depleted "fuel supply" constitutes the throughput which is processed in the finite-lifespan vortex (Carrier et al. 1971; Carrier et al. 1994). During processing, unless landfall over dry soil or orography intervenes, the throughput is refreshed against cumulus-convection rainfall by sea-to-air transfer of sensible and latent heat at a rate roughly characteristic of what would occur between the underlying ocean patch and the overlying atmosphere under ambient tropical conditions (i.e., as if the high-speed wind were not present). This hypothesis does not require that there is a greatly augmented sea-to-air transfer of sensible and latent heat under the high-speed portion of the vortex (Emanuel et al. 2004; Emanuel 2005). As discussed elsewhere in this minority report, *both* laboratory and at-sea measurement of the constancy, even decrease, of the drag coefficient at the sea-air interface, with higher wind speed, *and* the negative feedback on sea-to-air transfer owing to vortex-induced mixing and heat redistribution within the ocean underlying the high-speed portion of the vortex, are consistent with skepticism about a large ocean heat source.

We also believe that the restructuring of the core of the vortex (such that an eye is inserted within an eyewall, upon intensification from the tropical-storm-magnitude peak sustained wind speed to hurricane-magnitude peak sustained wind speed, and such that the depth of eye insertion increases with further intensification from hurricane-magnitude to major-hurricane-magnitude peak sustained wind speed) is not a coincident happenstance, but an essential feature of the transition. The insertion of an eye appears to be a sufficiently rapid event that it has been very rarely, if ever, adequately observed, owing to the noncontinuous monitoring of the core of tropical cyclones below the cirrus shield, which impedes optical access by higher-resolution sensors borne by satellites. Nevertheless, continuous monitoring of the core of a tropical cyclone to ascertain the presence, depth, and radius of the eye, and of the configuration of the eye/eyewall interface as a function of height, warrants high priority as an indicator of current intensity, and as a precursor of future intensity.

We are aware of current interest in observing, and roughly replicating with numerical models, rainband patterns observed in tropical cyclones. We are also aware of current interest in equipping reconnaissance aircraft with stepped-frequency microwave radar to infer surface winds, at least along the flight legs of the vortex-penetrating aircraft. Such data are of utility in characterizing the *existing* intensity of tropical storms. However, perhaps insufficient focus seems placed on: (1) continual monitoring that permits inference of the total static enthalpy as a function of altitude (from sea level to tropopause) at as many lateral positions as feasible from the center to the periphery of the tropical cyclone; and (2) continuous monitoring of the core of the vortex, through the depth of the troposphere, especially regarding generation and changes in the eye/eyewall geometry. We do not regard ourselves as qualified to “flesh out” this request, beyond remarks in the next section, but we regard the information as useful for forecasting *future* intensity, including eyewall-replacement cycles.

3.2 Novel sensors and platforms: an unprecedented Unmanned Aeronautical System

The two highest-priority challenges for operational forecasting of tropical-cyclone intensity have been previously identified as: (1) anticipation of the onset of rapid large-magnitude intensification/weakening, and (2) anticipation of the onset of eyewall-replacement cycling. The physical mechanisms underlying these transitions remain largely unknown, aside from the rather obvious general observation that the structure of the core of the vortex undergoes alteration, *possibly* on the scale of a quarter-hour for the first-listed event, and 6-24 hours for the second-listed event. Since, again as previously stated, a great advantage for simplistic analysis/computation is to proceed with a tentative thesis about the physical mechanism(s) involved, modelers, who have yet to respond adequately to these well-known challenges, well may look to observations for key assistance.

Many of the sensors and platforms anticipated to be available for monitoring tropical cyclones during the next five years have already been available for several years. During this interval, no significant progress on hurricane-intensity forecasting has been achieved through the contribution of these sensors and platforms. There appears to be reasonable doubt that continued exclusive use of these sensors and platforms is likely to result in a *major* breakthrough with respect to (for example) the two highest-priority challenges presented above. Accordingly, attention is turned to novel sensors and platforms that could advance rapidly from exploratory use to operational implementation to assist hurricane-intensity forecasting.

Owing to intensive investment through resources of the Department of Defense, Unmanned Aeronautical Systems (UASs) now reliably and routinely execute sophisticated military missions. As test prototypes and first-generation operational UASs are retired in favor of later models with enhanced capabilities, the earlier craft may become available for civil-sector applications, including the remote sensing of hurricanes. Of course, a civil-sector infrastructure must be developed for launch/recovery, in-flight control, and maintenance, but over-ocean flight should be less regulation-constrained. Developing this infrastructure and a cadre of skilled personnel would require time measured in years rather than months, and ought to be initiated forthwith, if the use of UASs for the remote sensing of hurricanes is deemed of high promise.

Attention is here focused on the fast-flying (jet-powered, ~350 kts), high-flying (~20-km altitude), long-loitering (~36-h mission duration) Global Hawk UAV, which is capable of carrying an instrument/dropsonde payload of roughly a thousand kilograms, though a tradeoff with other mission parameters establishes the precise value (MacDonald 2005). Relieved of concern for pilot availability, boredom, exhaustion, and safety, such a craft could swiftly reach the site of even a distant tropical cyclone, fly over the top of the vortex with exceptional stability in turbulence, and continuously hover over the core of the storm, to monitor changes in structure. Moreover, development is advanced on a small autonomous UAV called the Killer Bee with a two-or-three-meter wingspan) to be launched from a Global Hawk (as well as from ground or ship or other aircraft). One ~50-kg carbon/Nomex model of the Killer Bee has 12-26-h endurance, 7-15-kg payload, and an engine with 8 hp at sea level. Global Hawk/Killer Bee tandem provides a system capability for *sustained* simultaneous monitoring of the core of a hurricane, both near sea level and near the tropopause.

The Global Hawk/Killer Bee tandem, in conjunction with the NOAA Gulfstream IV, also provides platforms from which sensors could continuously measure the temperature and moisture through the depth of the vortex, from tropopause to sea level, at various lateral distances from the center of the vortex, extending all the way to the periphery of the system (i.e., in the tropical ambient surrounding the storm). Particularly useful would be accurate measurements of the moisture content of the midtroposphere (i.e., at altitudes in the vicinity of 700 hPa).

In continuously both monitoring the core of the vortex and probing the stratification of the air in the vortex, the Global Hawk system would be furnishing precisely what current observating capacity does not provide, information with the most promise for significantly advancing operational intensity forecasting for circumstances in which such forecasting currently is most challenged.

4. Laboratory Experiments

4.1 Rationale for laboratory experiments in conjunction with field experiments

The contribution to the understanding of tropical-cyclone phenomenology derived from field experiments is long established, and well appreciated among hurricane researchers and forecasters. Field observations have made fundamental contributions to the recognition of rainbands, eyewall-replacement cycles, roll vortices in the surface inflow layer, persistent warm-core eddies separating off from the Loop Current, etc. The element of surprise in the yield of at-sea experiments remains a major reason for continuing pursuit of field observations. Elsewhere in this report we advocate the extension of at-sea exploratory research (for rapid transition to operational intensity forecasting) through the introduction of high-flying, long-loitering UASs, to seek onset criteria for both rapid intensification and eyewall-replacement cycling.

However, at-sea experiments (recent examples of which include CBLAST for examination of phenomena at the air/sea interface, particularly under the high-speed portions of tropical cyclones, and RAINEX for examination of rainband/eyewall interactions in tropical cyclones) are costly to undertake, entail prolonged planning and drawn-out data reduction, and, accordingly, occur only at long intervals. Sometimes the carefully prepared experimental agenda ends up incompletely executed. Among the challenges of at-sea experiments are: difficulty in defining conditions (which typically cannot be prescribed at will, and typically are not controllable, maintainable, or repeatable); often-harsh environment for sensors and platforms; and inflexibility to respond to unexpected observations.

What seems less frequently undertaken in the tropical-cyclone research community is integration of laboratory-scale experimentation within a field-experiment initiative. Generally, lower-cost laboratory-scale experimentation may be pursued at the beginning of an initiative, and between at-sea data-collection campaigns, to evolve tentative theses. These theses may then be confirmed, modified, or rejected in subsequent at-sea testing. The large number of laboratory tests that may be executed with rapid turnaround and with relatively complete, relatively readily repaired instrumentation ought to permit a preliminary sorting of ideas. In direct contrast with typical at-sea conditions, a test environment in the laboratory may be well defined, controlled, maintained, and repeated as desired. Owing to the smaller number of tests typically executable at sea, "field" testing seems a less suitable environment in which to initiate a sorting of ideas and to undertake an exhaustive, systematic variation of test conditions. Rather, in proceeding to "field" experiments, attention may be focused on the modifications, if any, introduced by phenomena not reproducible in the laboratory, such as effect of very large Reynolds number and the role of stratification of the ambient. This protocol should not be construed as downplaying the role of "field" testing but rather as contributing an additional set of tools to the measurement enterprise.

4.2 A proposed extension to an existing laboratory experiment

Mark Donelan of the University of Miami (Donelan et al. 2004) has measured non-intrusively, in a combination of wind tunnel (up to 30 m/s) and programmable wave tank (1 m x 1 m x 15 m), that the drag coefficient at the air/sea interface does not continue to increase with the atmospheric-wind speed for storm-force and stronger winds. Rather, the drag coefficient remains constant with further increase of the applied wind. The laboratory result was found to hold up in sea trials conducted as part of the CBLAST experiment. In fact, in the presence of spray and surface waves at sea, the drag coefficient measured at sea was found to decrease modestly with increase of wind speed into the hurricane range. This provides an excellent example of how prior laboratory experimentation well served a subsequent trial at sea.

The surface boundary layer, a practically important portion of the hurricane that may be directly encountered by shoreline residents after landfall, is amenable to laboratory experimentation. Accordingly, we concur with Donelan that the dynamic experiment ought to be extended to encompass heat and mass transfer from slightly warmed water to moist air flowing above. It appears feasible to resolve experimentally the long-standing uncertainty about how the turbulent exchange coefficients for temperature and moisture vary with wind speed over the same flow range previously examined for the drag-coefficient results just discussed. With definitive laboratory results in hand, guidance should be provided about how to undertake at-sea testing to resolve at last this long-debated key boundary condition for the hurricane-modeling community.

The potential uses for a suitably generalized wind-wave tank experiment go far beyond the determination of some exchange coefficients in existing numerical models. In view of the limited amount of detailed information available about the air-sea interface, an appropriately designed experiment could furnish a vast amount of data about the nature of an air boundary layer evolving over a sheared layer of water, the two-phase interface being free to deform as it may. While the basically rectilinear flow in a wind-wave-tank boundary layer clearly differs from the swirling inflow in the ocean-adjacent boundary layer of a hurricane, there is no barrier to solving the same model equations for the geometry and boundary conditions appropriate to a laboratory experiment. Given appropriate instrumentation, then a vast amount of data regarding velocity, temperature, and moisture could be made available for comparison with predictions using both current and future forecasting models. This is an activity that should be pursued, and that takes advantage of a modification of an existing experimental facility.

Moreover, the boundary-layer predictions of a hurricane code with even less modification could be compared to observations made in another experimental facility constructed to simulate the swirling axisymmetric inflow above a liquid-filled tank under strong vortex forcing. In light of the scale of the above-cited apparatus of Donelan, formation of a study group to produce concrete recommendations about a feasible design for a circular wave tank of order 20-m diameter is recommended. Without intending to intrude on the work of experts in creating such a large experimental facility, we venture that it may be possible, perhaps through the use of vanes, to introduce air with angular momentum at the periphery of the tank, and to extract that air near the center of the tank. By making the water warmer than the air above, buoyancy could contribute, if not entirely suffice, to exhausting the throughput air. We emphasize that the objective concerns creation of a *swirling flow boundary layer over a pool* (Carrier 1971a), the configuration having features roughly in common with the *very-low-level flow* in a hurricane. (Attempting to simulate the entire hurricane structure is *not* being advocated.)

5. Organizational Issues

5.1 Need for restoration of a National Hurricane Research Laboratory

Today there exists within NOAA a research arm, the National Severe Storms Laboratory (NSSL), and an operational-forecast arm, the National Storms Forecast Center (NSFC), both collocated in Norman, OK, to serve the needs of the user communities concerned with severe local storms. Correspondingly, a highly advisable organizational step is the *restoration* of laboratory status (Rosenthal 1974) to a focus within NOAA of all hurricane-related research, both analysis/computation for modeling and instrument/platform development. The current subordination of a Hurricane Research Division (HRD) within the Atlantic Oceanographic and Meteorological Laboratory (AOML) obscures the fact that NSSL presently has about twice the number of staff as HRD, and in the past the ratio of staff at NSSL to staff at HRD has been even more skewed than that (F. Marks and J. Snow 2006, private communication). The proposed restoration of the National Hurricane Research Laboratory is intended to provide highly visible evidence of NOAA's commitment to programmatic unity and continual improvement in the monitoring and forecasting of hurricane track and intensity. The restoration affirms that modeling of tropical cyclones as a regional phenomenon will remain the viable pathway for NOAA indefinitely into the future. By the restoration, any suggestion that a regional approach to the modeling of internal hurricane thermo-fluid-dynamics is becoming anachronistic, to be replaced by subsuming hurricane modeling within global-scale forecasting, is rejected outright as being impractical on even the longest time horizon within the HIRWG's purview.

Housed within the Miami-sited NHRL ought to be: oversight of a revamped Joint Hurricane Testbed (JHT), discussed below; an enhanced Development Testbed Center (DTC), also discussed below; an effort, transferred from the National Centers for Environmental Prediction/Environmental Modeling Center (NCEP/EMC), to develop upgraded models; and a visitors program to initiate and sustain interaction with members of the extramural hurricane-research community. Just as a periodically reconstituted Science Advisory Board of extramural experts meets intermittently to offer guidance to the NOAA administrator, so NHRL should have its own periodically reconstituted, intermittently convened science advisory board to offer guidance to the NHRL leadership. From such an NHRL, a spectrum of mutually reinforcing models may be expected to evolve to serve the needs of the spectrum of users of hurricane forecasts. Nevertheless, a major fraction of the staff and resources of NHRL should be dedicated to the development of better instrumentation and more proficient gathering of observations on tropical storms and hurricanes.

We reiterate for emphasis that we have identified as a gap the absence of a focus for hurricane-research efforts within NOAA, with the many ongoing activities having become underfunded, spatially disperse, and sometimes isolated from (and impractical for) serving the objective of rapid transition to operational forecasting of hurricane track and intensity. Accordingly, we have recommended that NOAA restore the HRD to its former scope and status, so a strong adequately-funded NHRL in Miami becomes a center of excellence for: (1) hurricane modeling, that provides timely and accurate guidance regarding the evolving intensity of already-well-organized tropical cyclones; and (2) development, deployment, and utilization of diagnostic instrumentation for hurricane monitoring.

We now append several specific actions that ought to occur in connection with the restoration of the NHRL. The most obvious action recalls that, in the past, the operational arm for hurricane-intensity forecast and the research arm for hurricane-intensity research were collocated. For non-technical reasons, the arms are now situated nearly an hour travel-time apart in Miami. This separation in physical location impedes technical interchange and the efficiency of working relationships. To facilitate and accelerate research-to-operations transition of next-generation, upgraded products, the collocation should be restored forthwith. Collocation ensures that the research effort remains responsive to operational needs, and that the operational activity maximizes its awareness of (and input to) innovations “in the pipeline”. Furthermore, the interchange of personnel between the two arms in recent years suggests that some highly skilled and experienced staff seek to participate in both research and operations, and would be better accommodated. A more-closely-affiliated NHRL/NHC, having developed its own predominantly homegrown hurricane models, should be entirely self-reliant if necessary. Otherwise, NHRL/NHC may harbor uncertainties about the inner workings, approximations, and limitations of computer-produced intensity forecasts because those forecasts were generated by exercising “black boxes”, either elsewhere within NOAA, or outside NOAA by some knowledge-oriented organization without responsibility for timely accurate forecasting.

Next, NOAA ought to provide the resources (personnel, computing facilities) to carry out the formidable tasks of: selecting representative tropical-cyclone-simulation software yielding intensity forecasts; assembling historical data on the environment of a representative set of hurricanes, to serve as initial conditions and along-track boundary conditions for test runs; executing test runs, and comparing the computer output with recorded observations; and identifying shortfalls, and making objective recommendations concerning the suitability of each code for further NOAA investment as a candidate for transition to operational-intensity-forecast use by NHC. In light of earlier statements on numerical models and resolution (Section 2.1), a reasonable anticipation is that some of the representative codes will emerge from this preliminary sorting as sufficient to describe the outer, bulk vortex, though not the surface boundary layer or the core. But any candidate will need extensive real-time testing, extensive “tuning”, and extensive remediation, before being suitable to provide useful guidance to NHC staff for intensity forecasting. NOAA and NCAR jointly sponsor a very modest Development Testbed Center (DTC) in Boulder, but the just-enumerated tasks require a far greater commitment of resources. Furthermore, since NOAA expertise in hurricane observation and operational forecasting resides in Miami, plausibly an expanded hurricane-dedicated (component of the) DTC should be collocated there too, as part of the NHRL.

Also, the NOAA Strategic Plan proposed the formation of testbed centers to facilitate the transition of research results to operational forecast centers. The Joint Hurricane Testbed (JHT) was one of the first such testbeds. Approximately 75 past projects have produced modifications that have been adopted for NHC operations, and results from another 27 JHT projects are now being tested (R. Elsberry 2006, private communication). Because improved hurricane-intensity forecasts are the top JHT priority, many of these projects have directly or indirectly addressed this point. Many, if not most, of the projects have addressed readily implemented remediation for flaws and/or omissions identified in previously adopted NHC forecasting aids and procedures. Management of the JHT (selection of priorities, review of proposals, oversight of performers, etc.) has taxed the small staff of overburdened forecasters at NHC; in fact, testing of JHT results was suspended during the active 2005 Atlantic hurricane season. Since the accuracy of NHC tropical-cyclone-intensity forecasts has not improved significantly since the implementation of JHT-project products began, the purported positive impact of the JHT on intensity forecasting is moot. Moreover, the DTC, not the JHT, is the proper mechanism for testing completely new hurricane-intensity computer models; the JHT structure and capabilities are not appropriate for this task. Furthermore, the law of diminishing returns may be expected to hold for efforts to find simple fixes for fundamentally limited, in-place, operational-forecast-guiding procedures. Subdividing the JHT resources among many projects may enlist broad support for the program among principal investigators and their institutional affiliations; however, the hazard posed by hurricanes to the nation relegates such expediency to insignificance. Instead of continuing to subdivide the few-million-dollars budget of the JHT into many modest slivers, it makes more sense to stop constraining performers to work within the limits of ongoing practice. Perhaps half the JHT funding ought to be awarded to a performer to address an NHC-specified practical operational goal (especially one related to intensity forecasting), without constraint on the performer with regard to methodology. The other half of the JHT funding ought to be awarded to an institution (possibly a NOAA laboratory, more likely an extramural organization in the Miami area able to provide some co-funding) to design, build, instrument, test, and use a novel facility to carry out experiments elucidative of *aspects* of hurricane phenomenology (see Section 4). Such a dedicated facility, housed by an extramural organization, would create a targeted-research vehicle through which NSF, ONR, and/or NASA could co-participate with NOAA. This two-part use of the JHT funding may be expected to create ongoing centers of excellence in practical work on hurricane phenomenology. Of course, the two activities could be pursued at the same organization. Oversight of both activities might be better carried out by the research arm, rather than the operational arm, of NOAA's hurricane-related effort in Miami, because neither activity is aimed at very-near-term implementation for operational forecasting.

To avoid a proliferation of administrative staff in the proposed NHRL and to ensure a maximum of coordination between the work of the DTC (concerned with *inhouse* evaluation/advancement of existing hurricane-forecasting codes) and the JHT (concerned with NOAA funding of *extramural* hurricane-related mission-targeted research), we suggest that the oversight of the two programs be combined. In time, we anticipate that the two activities may meld, naturally and beneficially, into a single integrated NHRL program, without substantial alteration in the proportion of resources expended within NOAA and expended extramurally. With dedicated management, a reinforcement between work carried out within NHRL by NHRL staff and outside NHRL by members of the broader hurricane-research community should be realized.

Finally, it is unacceptable that almost no ongoing measurement-focused initiative (e.g., to assist the design and preliminary testing of instrumentation) exists among NOAA intensity-forecasting programs, which strongly emphasize computer modeling. A less computer-oriented outlook might increase the rate of transition to operational use of novel instrumentation, which might be advanced initially to serve the needs of laboratory experiments.

5.2 Collaboration with the National Severe Storms Laboratory and National Storms Forecast Center

In an era of austere Department of Commerce budgets, in which branches of NOAA either have reduced staffing (such as HRD) or add but limited staffing (such as NHC), temporary exchange of technical personnel within the agency may interchange fresh ideas, novel perspective, and a wider range of technologies. Personnel exchanges between the operational arms National Storms Forecast Center (NSFC) and NHC, and between the corresponding research arms National Severe Storms Laboratory (NSSL) and (the proposed) NHRL, seem feasible, especially outside of peak season, since everyone involved addresses severe vortical (cyclonic) storms in a locally convectively unstable troposphere. Not only do thunderstorms, cumulonimbi, and tornadoes arise within tropical cyclones, but it is now well documented by field observations that two-cell structure (i.e., eye-within-an-eyewall structure, albeit on vastly reduced lateral scale) attends long-lived, long-path, intense tornadogenesis in mesocyclones (Dergarabedian and Fendell 1976; Lemon et al. 1982; Carrier et al. 1994; Wurman and Gill 2000; Lee and Wurman 2005). Logistics may impede such temporary reassignments, but career-advancement incentives by NOAA management should ensure that, for example, radar-technology insights of Miami staff members benefit local-severe-storm forecasting, and numerical-modeling insights of Norman, OK staff members benefit tropical-cyclone-intensity forecasting. Because recent observations reinforce the commonalities between tornadogenesis in mesocyclones and hurricane evolution from tropical storms, the long-recognized shared features between tropical storms and severe local storms provide motivation for, and expectations from, personnel exchanges between NHC and NSFC, and between NHRL and NSSL. NOAA ought to benefit from the resulting more broadly knowledgeable technical staff/management.

5.3 Interaction with extramural research groups; human resources development

The approach adopted throughout this minority report on upgrading forecasts of the intensity of tropical cyclones is that of “regional modeling”. To us, the phrase means that it is useful to isolate conceptually the hurricane-containing volume (say, that portion of the troposphere within a finite-radius right circular cylinder or other conveniently shaped domain centered on the axis of the vortex)… though this isolation should not be regarded too literally and rigidly. For example, the volume containing the hurricane plausibly has the air-sea interface as its bottom and the local troposphere as its top, and the lateral faces of the domain lie far enough from the axis of rotation so that the winds have subsided to ambient. It seems helpful in addressing hurricane phenomenology to concentrate predominantly on the thermo-fluid-dynamic processes occurring within the volume, as a finite supply of convectively unstable air is processed once through the vortex until the supply is exhausted and the no-longer-self-sustaining vortex decays in a finite time (Fendell 1974). Changing conditions holding on the boundary of the container determine by how much the (specific) static energy (Palmén and Newton 1969) of the throughput supply is supplemented above the starting value or is depleted. Such changing conditions relate to: landfall, especially on a mountainous coast; the inducing of a circulation that cools a relatively thin mixed layer in the underlying ocean; the encountering of a strong vertical wind shear [change with height in the magnitude and direction of the ambient (zonal) wind]; etc. *Input regarding any change in conditions holding on the boundaries of the volume must be furnished for the envisioned modeling from efforts addressing larger-scale atmospheric modeling/observation, and from efforts addressing oceanic modeling/observation for the underlying sea. We envision the enhanced NHRL soon becoming appreciably more self-contained regarding modeling/observation of phenomenology within the hurricane volume than the current HRD… with a caveat now discussed.*

What occurs within the hurricane-encompassing volume typically involves much higher flow speeds and much stronger convection than is commonly encountered in the troposphere; and require special expertise. In fact, the flow speeds may be closer to those frequently treated by subsonic aerodynamicists than those frequently treated by many meteorologists. In recruiting staff and counsel regarding tropical cyclones, NOAA is advised to contact applied physicists, mechanical engineers, and others drawn from the broader fluid dynamics community. Indeed, some current members of the staffs of HRD and NHC studied mechanical engineering. Today, with greater emphasis on NOAA's undertaking goal-oriented, mission-directed research (as distinct from basic research), and on NOAA's achieving rapid transition of research products to operational use, an engineering background in fluid dynamics and heat transfer may be particularly relevant for pragmatic, yet fundamentally sound work on large intense vortices in highly convectively unstable atmospheres, both for approximate analyses/computation and for observation/experiment. Our participation on the HIRWG suggests to us, as outsiders, that an inordinate focus is placed on highly detailed numerical simulation, irrespective of its compatibility with available computing resources, among many meteorologically trained modelers. An altered composition of the NHRL staff appears to us to be conducive, if not mandatory, to broadening this focus.

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